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HYPOTHESIS OF SOLAR CORPUSCULAR STREAMS WITH FORCE-FREE MAGNETIC FIELDS

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HYPOTHESIS OF SOLAR CORPUSCULAR STREAMS*
WITH FORCE-FREE MAGNETIC FIELDS

(Gipoteza o korpuskulyarnykh solnechnykh potokakh s bessilovymi magnitnymi polyami)

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ABSTRACT

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Expounded is a hypothesis of solar corpuscular streams acquiring in the magnetic field of active regions a force-free magnetic field. The latter determines the stability of the stream at its generation and flow from the Sun toward the Earth. The magnetic energy of such a stream exceeds its kinetic energy. The conditions of outflow of the stream are determined by the interaction with the varying magnetic field of the active region. The structure in the interplanetary space of a corpuscular stream with a force-free magnetic field is examined. The qualitative scheme of such interaction of a geo-effective stream with the magnetosphere and the Earth's ionosphere is analyzed.

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COVER-TO-COVER TRANSLATION

Attempt is made in the below-expounded hypothesis to explain a series of peculiarities of the geomagneto-ionospheric perturbation by magnetohydrodynamic properties of the corpuscular stream resulting from the conditions of its generation and outflow from the active region of the Sun. The foundation of this hypothesis lies in the fact that a geoeffective solar corpuscular stream does not bear a frozen-in magnetic field, but has its own force-free magnetic field of a weakly-attenuating closed current of the stream. The stream's magnetic energy exceeds in this case its kinetic energy, and this determines the stability conditions and the stream's outflow from the active region, as well as its interaction with the magnetosphere and the ionosphere of the Earth. Although a quantitative analysis of certain aspects of this hypothesis is possible, only its qualitative aspects are considered in the present work.

Recent numerous observations made it clear that all the combination of phenomena in the active regions of the Sun is determined by the development of local magnetic fields [1 — 4]. This becomes evident as a consequence of the fact that the solar atmosphere, where all these activity phenomena take place, constitutes a plasma, and this is corroborated by a multitude of heliophysical observations. It is obvious that the generation and outflow of the geoeffective solar plasma (corpuscular streams), as one of the manifestations of solar activity, is also determined by the development of local magnetic fields of the active regions of the Sun.

The only possible mechanism for the explanation of local magnetic fields' penetration into the chromosphere and the corona, where geo-effective streams are generated, is the convective bearing out of sub-photosphere layers of spot and floccule magnetic fields [5]. The ineffectiveness of the wave mechanism of magnetic field transfer to the corona is determined by the fact, that magnetohydrodynamic waves pass relatively fast to shock waves, and because of dissipation, they may only heat the upper atmosphere and the corona [6], but they cannot transfer the regular magnetic field. As a necessary corollary of chromospheric-coronal plasma compressibility it results that the moving cloud acquires it own force-free magnetic field [5]. A force-free character of the magnetic field of a plamsa cloud is also seen from the condition of magnetohydrodynamic stability in a system with a spiral symmetry [7], and from the computation of the magnetic field for the case of a circular cylindrical plasma cloud of $\sim 10^{10}$ cm radius, $\sim 10^{11}$ cm extent and $\sim 10^{8}$ cm^{-3} particle concentration [8], it follows that stability takes place if $\bar{H}_r$- component of the magnetic field near the cloud's boundary is ~ 50 gauss. A similar estimate of the field for the protuberance gives ~ 15 gauss. In connection with that let us note, that the measurements of magnetic fields in active protuberances [9—11] indicate that the intensity of the magnetic fields in them is of the order of several hundred gauss. Hence, the magnetic energy density exceeds by about two orders the kinetic energy density in an active protuberance, which is possible on condition that the magnetic field in it is force-free.

In this regard, corpuscular geoeffective streams differ from protuberances only by the order of magnitude of their characteristic parameters (extent, density, temperature), while the magnetic field generation mechanism may be analogus. The detection of large magnetic fields in active protuberances may be viewed as evidence that large force-free magnetic fields (of the order of several tens of gauss) may exist in corpuscular streams. The characteristic peculiarity of such a magnetic field is the fact that it is not frozen within the plasma, but rather is a field of a closed current system, flowing in the bounded parts of the cylindrical plasma cloud.

As is well known, see [2], a force-free magnetic field constitutes a state with minimum energy, i.e. it is stable in regard to small disturbances. In the presence of Joule losses in the plasma cloud, the decrease in the degree of ionization on account of recombination and other processes taking place at relatively prolonged motion from the Sun toward the terrestrial orbit and beyond its limits, the current will also diffuse its field. However, in this case the field dissipation is minimum, and the stability of the force-free magnetic field is preserved. It is shown in [5], that the force-free character of the magnetic field in a plasma cloud is an indispensable condition for the compressed plasma flow, in which the conditions for the Helmhötz flow are not preserved. The field of such a cloud may be represented as a twisted toroidal field reminding us of a magnetic field of a stellorator. The generation of the toroidal plasma cloud is graphically illustrated by the Bostik experiments [12]. Such kind of toroid will be unstable in in the bipolar magnetic field of the active region relative to the helicoidal twisting [13, 14]. The magnetic field, intensifying at such twisting, quickly reaches a sufficiently high value for the stability of the whole plasma cloud. At toroidal field twisting the inner magnetic "walls" of the toroid draw together. This may lead to the generation in the corona region of high-energy protons and electrons. The corpuscule acceleration at repulsion from the magnetic wall [15] results more effective in the corona region, where the injection energy for the accelerated particles is substantially lower than in the chromosphere. In the inner region of toroidal magnetic field twisting the high-energy part of the thermal protons and electrons of the coronal plasma will be accelerated. This may assure the required concentration $(\bar{n} \sim 10 \div 10^2\ \mathrm{cm}^{-3})$ of relativistic electrons $(\varepsilon \sim 10\ \mathrm{Mev})$ responsible for the type IV radiobursts [16, 17] and noise storms. High-energy protons, responsible for the ionospheric absorption in the polar cap, are generated simultaneously. Because of the synchrotron radiation the relativistic electrons in the magnetic field of the plasma stream will become after several hours thermal electrons, while high energy protons may be preserved a long time in the magnetic trap of the stream's field. A similar pattern of high-energy particles generation corresponds to the observed peculiarities of the type IV radiobursts [17, 18].

The formed force-free magnetic field may be computed by the works [19, 20]. The magnetic field for an axially-symmetric force-free field may be represented in the form of a sum of toroidal and poloidal fields, whose current systems have also the corresponding components.

According to [20], the magnetic field of the stream may be considered approximately as a field of the effective dipole at relatively great distance from the "core" of the stream ($r > 2a$, where a — is the radius of stream's twine). A similar approximation may be used for the computation of the character of plasma cloud interaction with the local magnetic field on the Sun and with the Earth's magnetosphere, when the stream reaches the Earth's orbit.

The investigation of the effect of a varying local magnetic field of the active region upon a plasma cloud with its own force-free magnetic field, constitutes in itself a nonlinear non-steady problem of magnetic hydrodynamics, near the type II problem of the work in reference [2].

In a general case a transition is necessary during its solution from the classical approach to the problem to the generalized one. This implies the substitution for the functions searched for ($\mathbf{v}$, $\mathbf{H}$, $\mathbf{E}$, $\mathbf{P}$ vectors) satisfying the conjunction of the magnetic hydrodynamics equations and boundary conditions, for the vector-functions searched for of a certain functional Gilbert space. The problem amounts to the solution of the system of integral identities for $\mathbf{v}$ and $\mathbf{H}$. However the analysis of such a general solution of the problem appears to be premature not only because of the complexity of the solution itself, but also because at present no estimate exists ~~of a~~ series of characteristic parameters of the plasma cloud, necessary for the finding of a general solution. To solve the problem of plasma cloud interaction with varying local magnetic fields of the active region, observation data are necessary on the distribution of magnetic fields in the active and eruptive protuberances and filaments, situated near the varying bipolar magnetic fields of active regions.

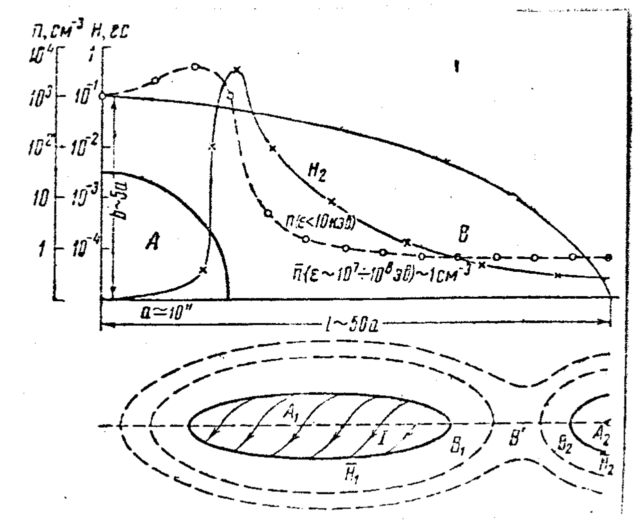
For that it is necessary to measure the total magnetic vector of the field in the active region (near the photosphere and in the chromosphere) and not only that directed along the visual field of the field component, as this is done now. Besides, measurement must be made of a series of spectroscopically obtained physical characteristics of the active regions on the Sun. Inasmuch as this kind of solution is still impossible, let us limit ourselves to the following remark:

By the strength of the relatively high characteristic dimensions of the highly-conducting geoeffective plasma cloud, the influence of the magnetic field of the active region does not spread over the cloud as a whole. If the inner part of the plasma cloud, where the magnetic field is nearly absent, is isolated from the effect of active region's field, its outer part, where a system of closed current flows, and whose magnetic field propagates far beyond the limits of the plasma cloud, will find itself under the effect of the varying magnetic field of the active region. The character of that influence depends upon the direction, structure and variation of the magnetic field in the plasma cloud, which is determined by the distribution of the magnetic field in the region where the steam was generated. This problem was solved semi-quantitatively in the work [22], where it is shown, that a concomittant action of vectors H upon the plasma, $d\mu/dt$ (where μ is the magnetic moment of the bipolar region) leads to a radial flow of the plasma mainly in the symmetry axis plane of the bipolar region, These results, corroborated by observations and applied in practice for the prognosis of magneto-ionospheric disturbance [23] must be re-examined, for the problem must be solved not for the plasma as a whole, but for a force-free field-bounded plasma cloud.

Up to now there was only question of formation and egress of a single plasma cloud. For a relatively long maintenance of the tendency to develop of the active region's magnetic field, a sequential egress of a great number of analogus plasma clouds may take place. They would follow one another, being interconnected by their own magnetic fields. The duration of such kind of corpuscular emission is determined by the development of electromagnetic fields above the active region of the Sun. The motion in radial direction of plasma clouds in sequence, and bearing their own force-free magnetic field, is determined by the initial effect of the electromagnetic fields of active regions, acting effectively to distances of $\sim 5 \div 6\ R_{\odot}$.

The stability of the plasma with force-free magnetic field assures the preservation of the flux of corpuscules so long as the current density and its magnetic field do not decrease significantly because of finite plasma conductivity (Joule losses). If at flux generation the appeared magnetic field were not too great ($\varepsilon_{mag} \leq \varepsilon_{kin}$), the decay of such a flux may begin significantly earlier than the corpuscular cloud would reach the Earth's orbit. The corpuscular flux decay is basically determined by the flux' own parameters (magnetic field intensity characteristic dimensions, plasma density etc..), and not by interaction with the interplanetary medium. In the first approximation the latter's effect may be neglected. This is conditioned first of all by the fact, that according to the latest investigations of the zodiacal light [24], the density of the gas component of the interplanetary medium, which was utilized by Chapman over the extended corona [25], was overrated by at least $2 \div 3$ orders. Direct rocket investigations of the far environment of the Earth lead to the same conclusion [26, 27].

On the other hand, the effect of a direct action by the rarefied plasma of the interplanetary medium is limited to the interaction with the outer part of the stretched magnetic field of the plasma cloud. In this case the "core" of the stream itself is nearly entirely isolated by its own magnetic field, and no variation in the current system of the corpuscular stream will take place. In the presence of low-density interplanetary gas ($n \sim 1\ cm^{-3}$), there appears at the periphery of the magnetic field of the stream a magnetic wall whose thickness is determined by the Larmor radius of particles with $10^2 \div 10^3$ ev energies, while ahead of the stream there forms a shock wave front. Inasmuch as even at the boundary of the stream $H^2/8\pi) > P$, steady tangential gaps are preserved at the boundary line between the stream and the interplanetary medium.



Protons with energies from units to hundreds of Mev will be found in the magnetic trap of the plasma cloud (beyond the bounds of the stream's core itself).

It may be admitted that the structure of the geoeffective corpuscular stream in the interplanetary space near the Earth's orbit has the form schematically represented in the graphs. Indicated are here the tentative characteristic parameters obtained from the condition of stream's magnetohydrodynamic stability. The relative dimensions have not been respected in the graph.

The variations of the spectrum of soft cosmic rays (from several hundred Mev to 2Bev) according to stratospheric measurements in time of magnetic disturances [28—30], just as the character and distribution of the type-III ionosphere absorption [31—32], may be explained by the presence of a magnetic trap around the core of the flux with trapped high-energy protons [33]. A similar analysis of data on the spectrum of the soft constituent of the primary component and on the distribution of the ionospheric absorption in the course of the entire geomagnetic disturbance may permit the obtention of certain quantitative characteristics of the stream's magnetic trap.

The first experiments in magnetic field measurements in the near-solar space with the aid of magnetometers installed aboard space rockets may be interpreted in accordance with the considered stream pattern. If the magnetometer conducted measurements at the periphery of the region B (Figure), it will register a relatively small magnetic field [34 —36]. Accounting for the course of magnetic field distribution far from the stream's core, it is clear that the measurement of field from tens to hundreds gammas is more probable than the detection of an intense (to $\sim 10^{-1}$ gauss) magnetic field near the core of the stream. During magnetic field measurements in the B region, the low-energy corpuscular flux measured say by means of ionic traps, must not increase significantly in comparison with that measured prior to nearing the stream. In cases when a rocket hits the core of the stream, the low-energy corpuscular flux may increase sharply for a small value of the magnetic field, for the latter is ejected from a highly-conductive core of the stream. A similar case might have occurred during measurements aboard the Soviet Venus probe [37]. Let us mention also that an analogus result was obtained on the American satellite "Explorer X".

Should these observations be corroborated in the subsequent experiments, an important aspect of the current working hypothesis would be demonstrated in principle, i.e. that the magnetic field of a stream is frozen in the plasma, but actually is a magnetic field beyond the bounds of the stream itself.

Let us note in connection with the above, that the traditional assertion of the fact, that the corpuscular stream carries along a frozen-in magnetic field is entirely inconsistent. Even the simplest computations show that the stretching of magnetic lines of force in the stream till the terrestrial orbit and beyond would have required a decrease to zero of the magnetic field of sunspots.

The exact solution of this problem amounts to the solution of the nonlinear problem of gradual filling of the whole space occupied by the stream by the magnetic field of the active region of the Sun. "The adherence" to the Sun of stream's lines of force necessarily leads in this case to the total change within 1 to 2 days of the magnetic field of the active region which is in clear contradiction with the observations.

A radially-directed field cannot be viewed as a simple stretching of the magnetic lines of force of the active region, for this would have made necessary a liberation in its generation region of energy significantly exceeding the possible energy egress in the Sun's atmosphere (including even the assumed thermonuclear reaction).

The question of interaction of a corpuscular stream of the considered shape (Figure) with the Earth's magnetosphere amounts to the solution of the type II - nonlinear magnetohydrodynamic problem of [21].

In order to obtain a general solution of the problem, it is necessary to conduct in the given case a qualitative analysis of the problem of stream's magnetic field interaction with the magnetosphere of the Earth. To that effect the geophysical observation data must be used so as to have the possibility of an optimum simplification of the general solution of the problem. Qualitatively, the character of that interaction is described by the following scheme: Geomagnetic disturbances within a broad frequency range occur at Earth's magnetosphere boundary contact with the leading edge or a lateral magnetic "boundary" of the field of the stream. Depending upom the vector of the aggregate magnetic field at the magnetosphere boundary, fast magnetic variations (transverse and longitudinal magnetohydrodynamic waves) and relatively small variations of the geomagnetic field occur at a specific time of the day. The idea of the so-called " magnetic storm families" brought out in references [41—43], has a natural explanation, according to the current scheme, The daily recurrence of geomagnetic disturbance periods appears when the Earth approaches or drifts away from the core of the stream, and is linked with a favorable addition of magnetic fields of the stream and of the Earth's magnetosphere. The analysis of the geographic distribution of amplitudes of separate families' perturbed periods would help in clarifying the structure and the quantitative characteristics of the stream's field. Whe the Earth gets relativley close to the core of the stream, an instability may appear in the latter, which according to [44, 45], will lead to the break away of plasma clusters from the stream. These are being instilled in the ionosphere along the magnetic lines of force, inducing magneto-ionospheric disturbances. The region of these plasma clusters injection is determined by the peculiarities of the distribution at great heights of the Earth's magnetic field. This probably also explains the predominating zones of negative ionospheric disturbances, and also the decreased frequency of such ionospheric disturbances in the F_2— region of the East-Siberian magnetic anomaly [46].

According to the present scheme, the Earth's radiation belts are not the original cause of geomagnetic disturbances, as this is assumed for example in references [47, 48]. It is not difficult to see, that even admitting the clearly overrated values of particle concentration in the belts, the energy of the magnetic storm is at least by two to three orders greater than the aggregate energy of all belts. According to the current hypothesis, the basic energy of the geoeffective stream is included in the energy of the magnetic field, which is partially transmitted to to the Earth's magnetosphere and ionosphere. The deformation of radiation belts, which sets in at time of contact of the Earth's magnetosphere with the magnetic field of the stream, may lead, for example, to aurorae, when the magnetic disturbance is weak, to ionosphere absorption and so for. However, variations in the radiation belts are secondary effects, and they cannot be the cause of diversity of perturbation phenomena of the whole complex of geophysical phenomena.

During the period when the Earth's magnetosphere enters in the region of the stream's magnetic field, a compression of the F_2— region of the ionosphere takes place. This leads to the so-called positive ionospheric disturbances. The effect of magnetohydrodynamic compression of the upper ionosphere and F_2- region, is sufficient to explain the observed positive ionospheric disturbance, as preliminary computations show. A series of morphological peculiarities of positive and negative disturbances may be explained within the framework of the currently studied scheme not only qualitatively, but also quantitatively. It must then be taken into account that the possibility of plasma instillation in the ionosphere in the form of clusters is not only determined by a sufficient rapprochement of the Earth's magnetosphere to the core of the stream, but also by directions in the corresponding periods of the magnetic vectors of the Earth and of the field. As was pointed out above, the latter is determined by the distribution of the magnetic field in the active region of the Sun, where the stream's generation took place.

The examined scheme of Earth's magnetosphere interaction with the magnetic field of the solar corpuscular stream may explain a series of peculiarities of cosmic ray variations, of aurorae and of other geophysical phenomena.

Let us draw some concluding remarks. The examined hypothesis may explain, at least qualitatively, the combination of factors linked with the generation on the Sun of geoeffective streams, and their action upon the Earth's magnetosphere and ionosphere. It is impossible at this time to point to a single experiment which would unilaterally demonstrate or reject the current hypothesis. That is why it seems most important to compute the distribution of the stream's magnetic field , which, as was pointed out earlier, may be effected by the geomagnetic data, the variation of the soft component of cosmic rays and the state of perturbation of the ionosphere, including the type III absorption.

The obtained values of the distribution of the corpuscular stream's magnetic field might be checked by direct measurements with the aid of magnetometers installed aboard cosmic rockets on the condition of obligatory knowledge of rocket's position relative to the "core" of the corpuscular stream.

The trustworthinesss of the examined hypothesis will be determined not only by the possibility of explaining already-known observation data. The current hypothesis allows to forecast certain peculiarities of of solar and geophysical phenomena which have not been observed as yet. This relates in particular to possible peculiarities of magnetic fields' distribution and motion in protuberances, wiewed as analogues of geo-effective corpuscular clouds and in the active regions of the Sun, and also to possible correlations (during separate periods) of amplitudes and distributions of geomagentic and ionospheric disturbances. This is scheduled to be accomplished later.

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